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RESEARCH MEMORANDUM

SURVEY OF SUPERSONIC INLETS FOR HIGH MACH NUMBER APPLICATIONS

By James F. Connors and John L. Allen

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

[redacted]

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RESEARCH MEMORANDUM

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SUMMARY

The various inlet design philosophies are assessed on the basis of recent experimental results obtained at Mach numbers up to 5. The basic compression systems (external, internal, and combined external-plus-internal) are compared for both Mach 4.0 turbojet and hypersonic-cruise ramjet engines. The inlet that appears best suited for the Mach 4.0 turbojet application is that with combined external-plus-internal compression. Because of the severe cooling and weight problems associated with variable geometry at hypersonic flight speeds, the fixed-geometry self-starting characteristics of external-compression systems may be the overriding factor in the selection of an inlet for the hypersonic-cruise ramjet.

INTRODUCTION

As design flight speeds are pushed progressively higher, the supersonic inlet becomes an increasingly important component of air-breathing propulsion systems. Currently, the turbojet engine is being considered for application at Mach numbers up to approximately 4 and the ramjet engine for application in the hypersonic region, or Mach numbers of 5 and above. Herein the inlet situation is surveyed and the merits of the various inlet-design philosophies are assessed on the basis of recent experimental data obtained at Mach numbers up to 5. These trends are then extrapolated into the hypersonic range for an analysis of the performance potentialities of the various ramjet inlet configurations.

GENERAL INLET DISCUSSION

The three basic types of compression system that will be considered are illustrated in figure 1. These schemes will be referred to according to their mode of compressing the flow - that is, external or internal compression relative to the cowl lip. External supersonic compression is accomplished outside the cowl by turning the flow radially outward by

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means of a protruding ramp or spike. The internal-compression scheme, on the other hand, accomplishes all the compression inside the cowl and is capable of high performance if the characteristic starting problem can be handled. In order to start a highly contracted supersonic inlet, complexity must be added in the form of variable geometry, because the contraction ratio between the entrance and the throat must be decreased drastically before supersonic flow can be established within the inlet. The lower sketch in figure 1 shows a system utilizing both external and internal compression. This scheme has a starting problem similar to that of the internal-compression configuration but not as severe.

In order to demonstrate graphically this starting problem, which is characteristic of any inlet employing large internal contraction, and to illustrate the shock - boundary-layer interactions that occur within the inlet duct, selected frames of a motion-picture sequence of a two-dimensional inlet with external-plus-internal compression at Mach 3.05 are shown in figure 2. This configuration was similar to that schematically represented in the lower sketch of figure 1, but had a variable bypass door ahead of the throat to permit starting. Rectangular glass sideplates were installed on the model to allow schlieren observations of the flow inside the inlet. Figure 2 illustrates one complete cycle of the starting procedure, which must be repeated each time the terminal shock is expelled. Note the extensive separation occurring in the vicinity of the terminal-shock system (fig. 2(d)) during supercritical operation. The point of incipient separation moves forward towards the throat as the back pressure is increased until critical operation (fig. 2(e)) is attained. These observations accentuate the need for boundary-layer control in high Mach number inlets.

The geometry and performance variations obtained for these various compression systems will now be considered in detail. With respect to the inlet, the two parameters that best describe over-all performance are total-pressure recovery and external drag. This drag, of course, can consist of cowl-pressure drag, additive or spillage drag due to flow deflection ahead of the cowl lip, and bleed drag due to the removal of flow internally for boundary-layer control and its return to the free stream. Obviously, at any given Mach number, a good inlet would be one having both high recovery and low drag.

The interrelation between recovery and drag is examined in figure 3 for various flight Mach numbers. As determined in reference 1, the ordinate indicates the increase in drag coefficient (based on the captured free-stream-tube area) $\Delta C_{D,A_c}$ that can be tolerated for a unit increase in pressure recovery $\Delta P/P_0$ in order to maintain a constant range. This is referred to as a range "break-even" condition. At low Mach numbers, a large increase in drag coefficient is permissible for a given increase in recovery. At high Mach numbers, only a small increase

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in drag coefficient is tolerable for the same increment in recovery. For example, the value of this parameter for Mach 2.0 is five times that for Mach 5.0. Thus, there is an increasing sensitivity to drag coefficient with increasing flight speeds.

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External-Compression Inlets

Historically, large amounts of experimental performance data have been obtained on the various types of external-compression inlets. Attention here (fig. 4) is on the most refined form of external compression - that is, an inlet utilizing a continuously contoured isentropic-compression surface. This inlet attains the highest level of recovery for all-external compression, but it also has a theoretical limit (ref. 2) based upon flow conditions at the compression-fan focus point. This limit on maximum compressive turning is determined by the requirements of a pressure balance and equal flow direction across the vortex sheet emanating from and immediately downstream of the focal point.

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Generally, peak recovery is attained when the cowl lip is alined with the local flow behind the compression fan. This results in an inclined lip, and hence drag. Thus, with increased turning, both recovery and drag would increase. In practice, compromises are usually made wherein an internal shock off the cowl is taken in order to reduce the cowl-lip angle.

Boundary-layer control for the external-compression inlet is provided by a ram scoop located in the throat. This is schematically represented by the circled sketch in figure 4. Significant performance gains may be attained with this type of bleed (see ref. 3 for two-cone-inlet results).

The inlet shown in the lower part of figure 4 is designed specifically for high Mach number application ($M > 4.0$). The cowl-lip drag is eliminated through a sacrifice in potential recovery by limiting the amount of external compression. This limit is determined by the requirements for shock attachment on a cylindrical cowl. At these high design speeds, the subsonic entrance Mach number is low enough to permit the use of an abrupt area discontinuity, or subsonic dump, without large loss in recovery. In fact, at Mach 4.0, the calculated turning loss for a cylindrical cowl with a constant-area throat section (as discussed in ref. 4) is about the same order of magnitude as this dumping loss, which is based on a recovery of the static pressure behind the normal shock alone.

Boundary-layer control through a rearward-facing flush slot is provided in the throat to handle any pressure feedback originating downstream. The possibilities of short length and light weight with this arrangement are obvious.

The theoretical recovery limits for these external-compression inlets are shown for a wide range of Mach numbers in figure 5. Reference lines of constant kinetic-energy efficiency η_{KE} (ref. 10) are also included. In the turbojet range of application, the theoretical limit for maximum turning is quite high, decreasing from 0.99 at Mach 2.0 to 0.68 at Mach 4.0. In the ramjet range, where kinetic-energy efficiency can be used as a guide, recovery levels corresponding to efficiencies of approximately 95 percent can be attained up to Mach 7.0. For the zero-cowl-drag, limited-compression case, kinetic-energy efficiencies of about 92 percent can be achieved. For this case, dumping losses are taken into account. The corresponding recoveries are based on a recovery of only the static pressure behind the normal shock, or a full loss of the subsonic dynamic pressure.

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Internal-Compression Inlets

Cowl-lip drags can be eliminated by using an internal-compression system that does not appear to have any theoretical limits on recovery. Two axisymmetric versions of this system are shown in figure 6. The upper sketch illustrates a configuration without any centerbody, which simply is a convergent-divergent diffuser with small included angles (approximately 8°). This inlet is quite long, 2 to 4 inlet diameters in the supersonic portion alone. This length is dictated by the necessity of maintaining small pressure gradients on the boundary layer in order to avoid separation difficulties. For starting, a large throat bypass is provided. After starting has been accomplished, boundary-layer bleed around the throat periphery and a constant-area section are generally needed for shock stabilization.

The lower sketch shows an internal-compression inlet that utilizes a small-angle centerbody that can be translated to vary the contraction ratio between the entrance and the throat. For starting, long translation distances are required, approximately 2 inlet diameters. Otherwise, this inlet is similar to the upper configuration, in that both are long because of boundary-layer considerations and both need throat bleed.

External-Plus-Internal-Compression Inlets

The all-internal-compression inlets do not appear attractive because of over-all length and spike-translation requirements. In comparison, several configurations using combined external- and internal-compression systems look somewhat better in this respect. These configurations are illustrated in figure 7. The top sketch shows an axisymmetric version having a low-angle centerbody. A cylindrical cowl is used with the lip located back on the initial conical shock. Internal compression is accomplished by a number of reflecting shocks in

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the gradually convergent passage ahead of the throat. With this inlet, the spike-translation requirement for starting is only about half that for the corresponding all-internal-compression scheme shown in figure 6. The over-all length of this inlet is still undesirable.

In the center sketch of figure 7, another axisymmetric version of the combined external-plus-internal-compression system is shown. This inlet has a larger-angle centerbody (e.g., a 20° half-angle cone at Mach 3.0 was used in ref. 5) than the top arrangement and accomplishes the internal compression of the flow through a system of shocks, generated by the internal cowl surface and focused on the sharp shoulder of the centerbody. Boundary-layer bleed is provided in the form of a flush slot ahead of the throat. In this case, the starting translation requirement for the centerbody is only a fraction of that required by the top inlet. The over-all length of this configuration is also much less than that of the top inlet.

In the bottom sketch of figure 7, a two-dimensional version of an external-plus-internal-compression inlet is illustrated. This configuration was used in the motion-picture sequence of figure 2. Briefly, isentropic contoured ramps are used to generate both external and internal focused compression with a low-drag cowl. A small variable bypass door is provided ahead of the throat to handle the starting problem. This bypass is a relatively small component of the over-all inlet system and, compared with translation or rotation of major compression surfaces, should be mechanically much simpler and faster. In the flush or design position of the bypass door, a small gap is left for boundary-layer bleed.

Experimental Results

Detailed performance data obtained with these various inlet geometries in recent experimental investigations are given in table I. Peak performance levels are indicated for each type of inlet. These experimental results are the basis for conclusions drawn in the succeeding discussion.

Experimental pressure-recovery levels obtained with the various inlet systems are indicated in figure 8. Bands of recovery against Mach number are presented and identified only by the basic type of compression system. The all-internal-compression systems attained the highest recovery levels, corresponding to kinetic-energy efficiencies greater than 0.97 with zero cowl-lip drags. However, with the attainment of these exceptionally high recoveries, there was an attendant large bleed requirement (e.g., 30 and 25 percent of the air entering the cowl had to be removed at Mach 3 and 5, respectively). When attempts were made

to reduce this bleed at Mach 5, the recovery correspondingly decreased. At this particular Mach number, a 6-percent-bleed requirement existed at the lower boundary and the recovery was down to 0.41. The rest of the inlets all had moderate bleed requirements (less than 10 percent of the inlet mass flow). Of the three systems, the external-compression inlets showed the lowest levels of peak performance. The maximum-turning case, however, still attained kinetic-energy-efficiency levels of 97 percent at Mach 2 and 95 percent at Mach 4. The cylindrical-cowl version indicated kinetic-energy efficiencies of 90 to 92 percent at Mach numbers from 4 to 5.

TURBOJET INLET CONSIDERATIONS

The preceding discussion has dealt only with the general inlet problem of attaining high pressure recovery with low external drag. In the application of these various geometries to the high Mach number turbojet, additional inlet operating problems such as the following arise: (1) subcritical operation, (2) angle-of-attack effect, (3) diffuser-exit flow distortion, and (4) engine matching. With the high-recovery inlets there is no stable subcritical operating range at design speeds. The high-performance external-compression inlets encounter "buzz" or shock instability, whereas the other types with large internal contraction suffer large performance penalties due to expelled-shock operation. All axisymmetric inlets with high recovery capability are sensitive to angle of attack, with rather severe losses occurring at angles of 5° or more. However, the inlets may be sheltered from angle-of-attack effects by favorable environmental locations on the airplane configuration, such as under the wing or under a flat-bottom fuselage. Design criteria for maintaining low distortion levels (refs. 6 and 7) have been established for Mach numbers up to 3 or 4. At the higher speeds, inlet data are generally lacking. Some consideration will now be given to the primary problem of matching an inlet to the high Mach number turbojet.

Engine Matching

The off-design matching requirements for the handling of excess inlet airflow are shown in figure 9 for a hypothetical Mach 4 turbojet engine operating with an assumed recovery schedule. Typically, large quantities of air must be diverted from the engine at the low Mach numbers (e.g., at Mach 2.0, as much as 70 percent of the possible inlet airflow must be spilled in some manner). This is entirely a function of the particular engine airflow schedule and is independent of any additional boundary-layer-bleed requirements. The efficiency of handling such excess air can be vitally important to the over-all powerplant performance at off-design speeds.

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The associated drag penalties in percentage of net engine thrust for the various methods of handling this excess air are shown in figure 10. The additive or spillage drags associated with diverting flow around the cowl by means of a bow shock or an oblique shock generated by a 30°-half-angle cone result in clearly prohibitive drag penalties. These values bracket those resulting from inlets having large-angle centerbodies (typical of the axisymmetric external-compression inlets). If the corresponding spillage were achieved through an oblique shock generated by a 15°-half-angle cone, the drags would be quite low. This would be the type of spillage achieved by the axisymmetric inlet with low-angle centerbody and external-plus-internal compression. Low drags may be achieved with the two-dimensional external-compression inlets, of course, by reducing ramp angle at the lower speeds.

The drags associated with taking the excess inlet air aboard and then returning it to the free stream by means of a bypass ahead of the compressor face are also shown in figure 10 for the conditions of sonic and full-expansion discharge. A thrust coefficient of 0.9, which corresponds to about a 15° discharge angle, was assumed in the calculation. Both bypass drags are somewhat higher than the oblique-shock values for a 15°-half-angle cone.

Other possibilities for handling excess airflows (which will not be considered here) include bypassing the excess air around the engine and using it in the base area, in the overexpanded portion of the exhaust nozzle, or even in conjunction with heat addition in the bypass duct for thrust augmentation (as in the turbofan engine).

Inlet Comparisons

The design-point characteristics of the various inlet systems for the Mach 4.0 turbojet application are summarized in table II. The three basic inlet types (i.e., systems with external, internal, and combined external plus internal compression) are compared on the basis of factors that would influence the selection of a particular geometry. Weak points in the argument for any inlet type are indicated by shaded areas within the table. The total-pressure recovery at Mach 4.0, as shown previously in figure 8, was highest for the all-internal-compression system with a maximum of 0.75, corresponding to a kinetic-energy efficiency of approximately 97 percent. The lowest recovery was realized with the external-compression scheme, which shows a maximum of 0.60, or a kinetic-energy efficiency of 95 percent. Cowl-lip drag, of course, was only a problem for the maximum-turning version of the external-compression inlet. This can be a big penalty; for example, at Mach 3, cowl-lip drag alone amounted to 10 to 12 percent of engine thrust. Variable-geometry requirements for starting were large for the

internal-compression scheme and somewhat less for the combined compression system. Boundary-layer-bleed requirements were moderate for all except the internal-compression inlet. This inlet, in achieving its exceptionally high recoveries, had an attendant large bleed requirement (25 to 30 percent of the maximum possible inlet airflow), which is far in excess of any airflow needed for secondary engine systems. If it were assumed that this quantity of bleed air were returned to the free stream by means of a bypass ahead of the compressor, even with a complete-expansion bypass nozzle, the resulting drag at Mach 4.0 would be about 10 percent of net engine thrust. The over-all length of the all-internal-compression system is also higher than that of the other systems.

Based on these qualitative results, the inlet that appears best suited for the Mach 4.0 turbojet application is that with combined external plus internal compression. The all-external system is eliminated because of its large cowl-lip drags, while the all-internal system is penalized because of its large variable-geometry and boundary-layer-bleed requirements and its high over-all length. The combined compression system offers the best compromise for the Mach 4.0 turbojet.

HYPERSONIC-RAMJET INLET CONSIDERATIONS

The attainment of good off-design performance for a hypersonic ramjet engine is even more difficult than for a turbojet engine, primarily because of the larger inlet and exit area variations required with the high design flight Mach numbers. The associated variable-geometry requirements are formidable problems because of the extreme temperatures.

If the engine is designed for good range at cruise, the excess thrust at below-design speeds is generally small. If the cruise engine is compromised in order to increase the excess thrust during self-acceleration, the penalties at the cruise condition are large. An alternative approach for some applications might be to use an expendable engine for the boost phase. This problem is beyond the scope of this study, and hence only inlets for on-design ramjet engines will be discussed.

Effect of Flight Mach Number on Ramjet Thrust and Drag Coefficients

The variation of design-point thrust and nacelle drag coefficients (based on capture area) for Mach 5 to 7 is shown in figure 11. For this and subsequent figures, the cycle calculations are for real gas properties for stoichiometric combustion of SF-1. The exhaust pressure is 2.5 times the ambient pressure. The velocity coefficient, defined as the ratio of the axial exit velocity to the ideal velocity for the

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stated exit pressure, is 0.97. Thrust coefficients are shown for inlet kinetic-energy efficiencies of 97 percent, which might be obtained with a high-pressure-recovery all-internal-compression inlet; 90 percent, which is obtainable with external-compression inlets; and 72 percent, which approximates normal-shock-inlet performance. The assigned boundary-layer bleed requirements of 20 percent for the high-efficiency inlet and 10 percent for the 90-percent kinetic-energy efficiency were optimistically extrapolated from lower Mach number experimental data. The normal-shock inlet requires no bleed, and hence the total drag for the engine is composed of friction and wave or external pressure drag, as shown by the shaded region of figure 11. Wave drag was calculated by the method of reference 8, and friction drag for radiation equilibrium temperature by means of reference 9. (Blunt-lip drag has not been considered but should be relatively small and not affect the relative comparison.) The friction and wave drags for the high-efficiency engine are of similar magnitude. However, the drag associated with discharging boundary-layer-bleed air can be from 2 to 4 times the sum of the friction and wave drag, depending on whether a sonic or completely expanded exhaust is used. The thrust coefficient decreases with increasing Mach number, while the drag coefficient remains nearly constant. Thus, drag becomes relatively more important at higher Mach numbers. The difference between the thrust and drag coefficients, or thrust minus drag, which must be equal to the drag coefficient of the remainder of the missile, decreases not only with increasing Mach number but also with decreasing kinetic-energy efficiency, particularly for efficiencies less than 90 percent. Thus, the required engine size would depend on the inlet kinetic-energy efficiency.

Effect of Inlet Type

Some of the interacting effects, such as level of pressure recovery, various drags, size, and weight, can be illustrated by designing engines with different types of inlets to provide equal thrust minus drag. A pictorial comparison is shown in figure 12 for Mach 7.0 and an altitude of 100,000 feet. The same "ground rules" such as nozzle and diffuser angles are used for all the engines. The combustor length is constant, and the engines are illustrated with combustors alined. Bleed-air passages are shown schematically, although the calculations were for full expansion with a nozzle coefficient of 0.9 at a constant bleed-air total temperature equal to free-stream stagnation temperature.

Engines A and B, having all-internal-compression inlets, are shown for a probably unrealistic recovery of 0.50 and for a recovery of 0.15. Both inlets have 10°-included-angle compression surfaces and are of approximately equal length. Although the high-recovery inlet has the greater compression, the normal shock occurs at a Mach number of about 2.4 compared with a Mach number of 3.6 for the 0.15-recovery inlet.

Because of these counteracting effects and the absence of experimental data, it is assumed that the boundary-layer bleed would be 20 percent of the capture flow for both inlets.

Two engines (C and D) having external-compression isentropic-spike inlets with a boundary-layer-bleed requirement of 10 percent are shown in figure 12. An inclined cowl lip having an area of 10 percent of the capture area is required for the inlet with 0.25 pressure recovery. The 0.10-pressure-recovery inlet had limited compression, zero cowl-lip drag, and a dump diffuser. A normal-shock engine (E) is shown for comparison.

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The relative sizes of the engines primarily reflect the effect of pressure recovery or kinetic-energy efficiency on internal thrust coefficient. Since the requirement is for equal net thrust or thrust minus drag, the various drag components also influence the size and will be discussed later.

Also shown on figure 12 are preliminary values of ratio of engine to missile gross weight. These values are for the primary structure and include regenerative cooling of the internal surfaces. In regions where the fuel pressure would not cause local buckling, a corrugated material is used. In regions where fuel pressure is high compared with air pressure, such as the inlet and nozzle, a circumferential wrapped-tube construction (similar to some rocket-engine nozzles) is used. A 0.05-inch thickness of zirconia is assumed for the combustor and a 0.035-inch thickness for the remainder of the internal areas. The coating surface temperatures are assumed to be 2000° R in the inlet and subsonic diffuser and 2500° R in the combustor and exhaust nozzle, where oxidation problems do not exist. A tensile-stress level of about 18,000 psi is used for Inconel X. In the interest of minimizing thermal-stress gradients, the outer skin is assumed to be supported only at the cowl lip and the nozzle exit. The mount for the engine is attached to the external skin, which is stressed for an engine weight of 3 g's. No allowance is made for controls, fuel pumps, manifolding, or variable geometry.

The weight ratio is influenced by both inlet type and pressure recovery. For example, the change in weight ratio for the engines having all-internal-compression inlets is primarily due to the ratio of internal pressures of nearly 3 (30 atm against 9 atm), since the sizes of the engines are about equal. In contrast, the normal-shock engine, which has a low internal pressure (0.6 atm), is very large and has the second highest weight ratio.

The engine with the 0.25-recovery isentropic spike has the highest weight ratio primarily because of the high load on the base of the spike

and the structure needed to hold the spike. It should be emphasized, however, that the weight factors neglected in this analysis would very likely result in heavier weights for the all-internal-compression engines because of the inherently needed variable geometry. In addition, more powerful fuel pumps would be required to raise the injection pressure above the internal pressure, and hence the weight of this item would be a function of both discharge pressure and flow rate.

The various drag components are presented as a ratio of drag to net thrust for these engines in the lower part of figure 13. The engines are arranged according to pressure recovery. For the normal-shock engine, friction is about 70 percent of the total drag because of the large surface area; the remainder of the drag is wave or external pressure drag. The largest portion of the drag for the other engines is due to bleed or cowl-lip drag for the high-recovery isentropic spike engine (configuration C). The sum of cowl-lip and bleed drag is of the same magnitude as the bleed drag for the all-internal-compression inlet, which was assigned the higher bleed requirement. However, both the amount of lip inclination and the length of alinement are also rather arbitrary assignments. Wave drag is not an important component except for the normal-shock engine previously mentioned. The relative heights of the drag columns represent the engine size increase needed to provide equal thrust minus drag.

In the upper part of figure 13 the range relative to that for the normal-shock engine is plotted as a function of pressure recovery for the various engines. In the basic range equation, the thrust minus drag is used in the impulse term and the effect of engine weight is accounted for in the logarithm term by maintaining a fixed ratio of fuel plus engine weight to missile gross weight of 0.5. As pressure recovery is increased from the normal-shock value of 0.011, the relative range increases rapidly to a value of about 2.2 at a recovery of 0.10 or a kinetic-energy efficiency of 90 percent. The relative range does not change much for pressure recoveries up to 0.25, and then increases slowly to a value of about 2.5 at a recovery of 0.50.

Thus, inlet kinetic-energy efficiencies greater than about 90 to 95 percent result in only small increases in range for hypersonic-ramjet missiles. Serious cooling and weight problems are associated with the variable geometry necessary to establish or start supersonic flow for the all-internal-compression inlet needed to obtain higher kinetic-energy efficiencies (greater than 95 percent). Even when these factors are ignored, the increase in range over that for the simple self-starting all-external-compression inlet is only about 15 percent.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, November 21, 1957

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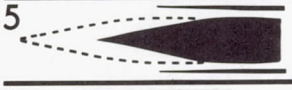
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	EXPERIMENTAL RESULTS				
	M_0	P_3/P_0	C_D cowl (ref A_{max})	$\dot{m}_{bleed}/\dot{m}_0$	$\dot{m}_{spillage}/\dot{m}_0$
1 	3.01 3.01	0.81 0.74	0.10 0.10	0.05 0.03	0.06 0.06
2 	3.85 3.85 4.95 4.95	0.41 0.47 0.33 0.23	0 0 0 0	0.08 0.25	
3 	2.97 4.95	0.88–0.91 0.59 0.415	0 0 0	0.29 0.25 0.06	0 0 0
4 	2.5	0.91	0	0.13	0
5 					
6 	3.01	0.78	0.01	0.02	0
7 	3.05 4.95	0.79 0.40	0 0	0.05	0

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TABLE I. - INLET RESEARCH

INLET TYPE →	EXTERNAL COMPRESSION MAX TURNING	INTERNAL COMPRESSION	EXTERNAL + INTERNAL COMPRESSION
RECOVERY LEVEL, M = 4	0.55 - 0.60	0.65 - 0.75	0.62 - 0.69
COWL-LIP DRAG	HIGH, 10 to 12% of F_N at M~3	0	0
VAR-GEOM REQUIREMENT FOR STARTING	0	LARGE	INTERMEDIATE
BLEED REQUIREMENT	0.03 to 0.05 m_0	0.25 to 0.30 m_0 at M_0 = 3 to 5	0.05 to 0.10 m_0
OVERALL LENGTH	MODERATE	LONG	MODERATE

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TABLE II. - MACH 4.0 TURBOJET INLET CHARACTERISTICS

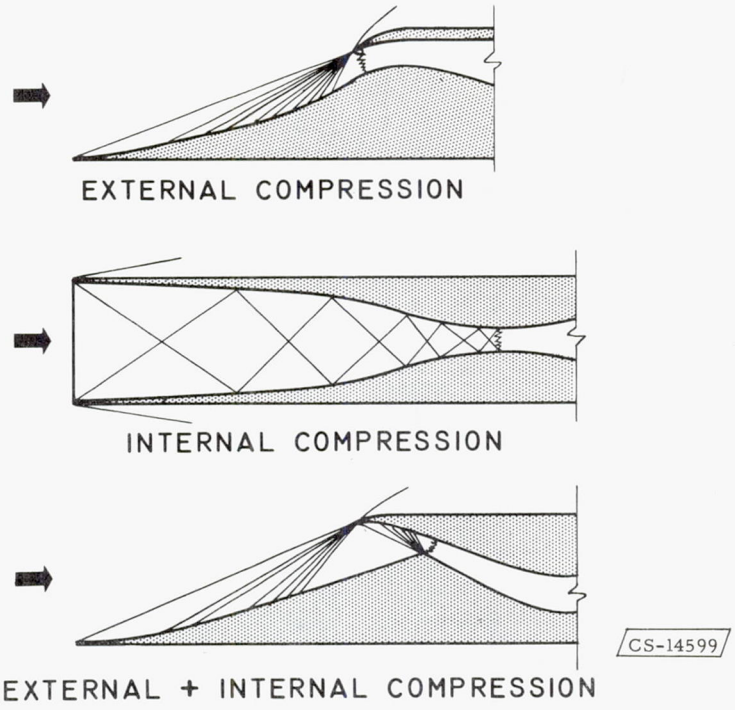


Figure 1. - Inlet compression systems.

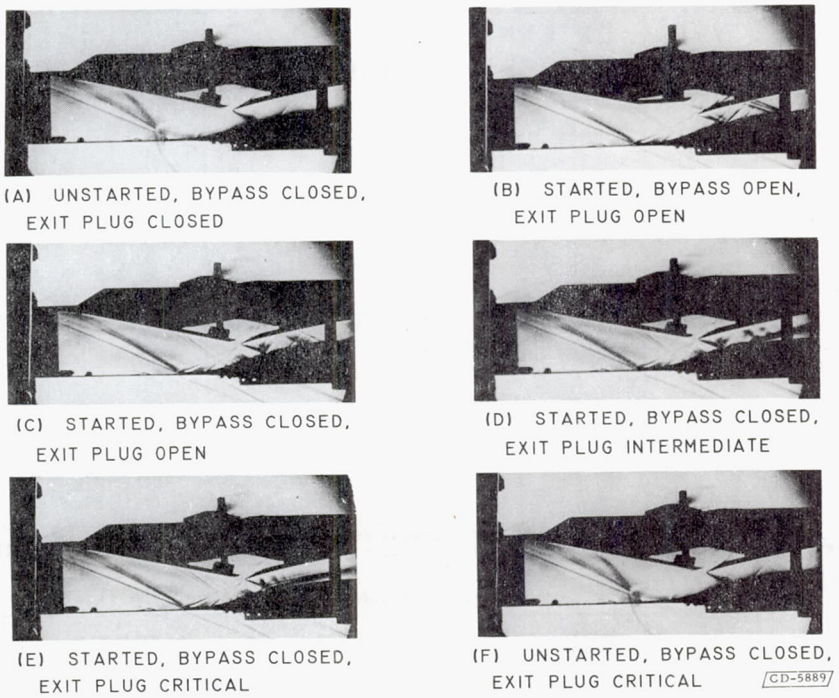


Figure 2. - Starting and operating procedure for two-dimensional inlet with external and internal compression. Mach number, 3.05.

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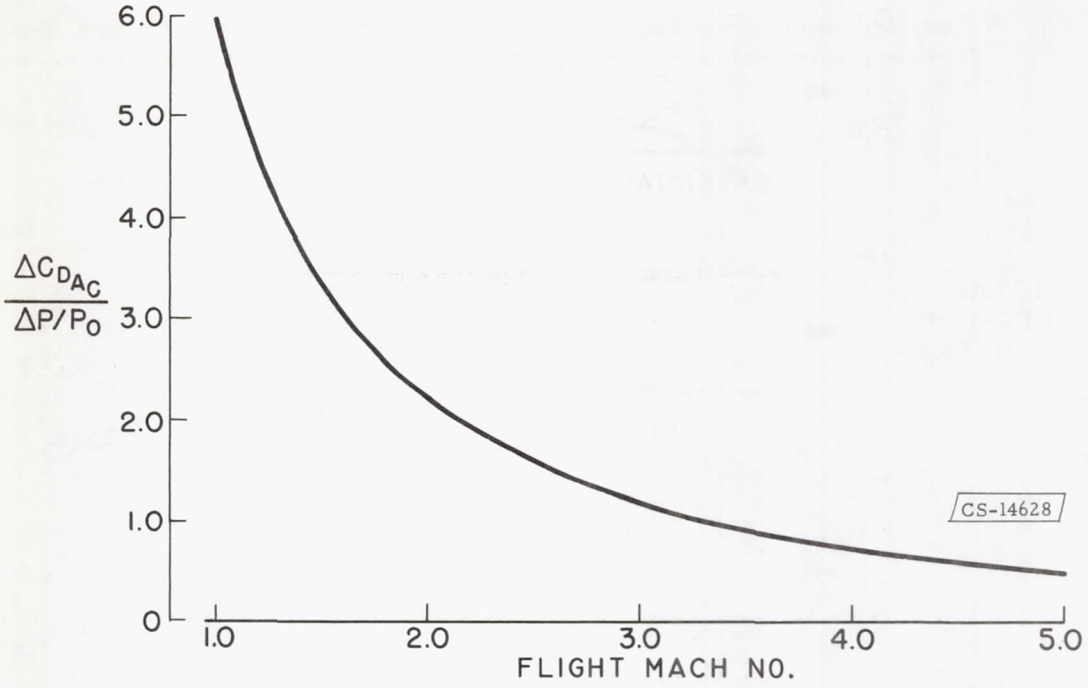


Figure 3. - Relation of pressure recovery and drag coefficient for range break-even.

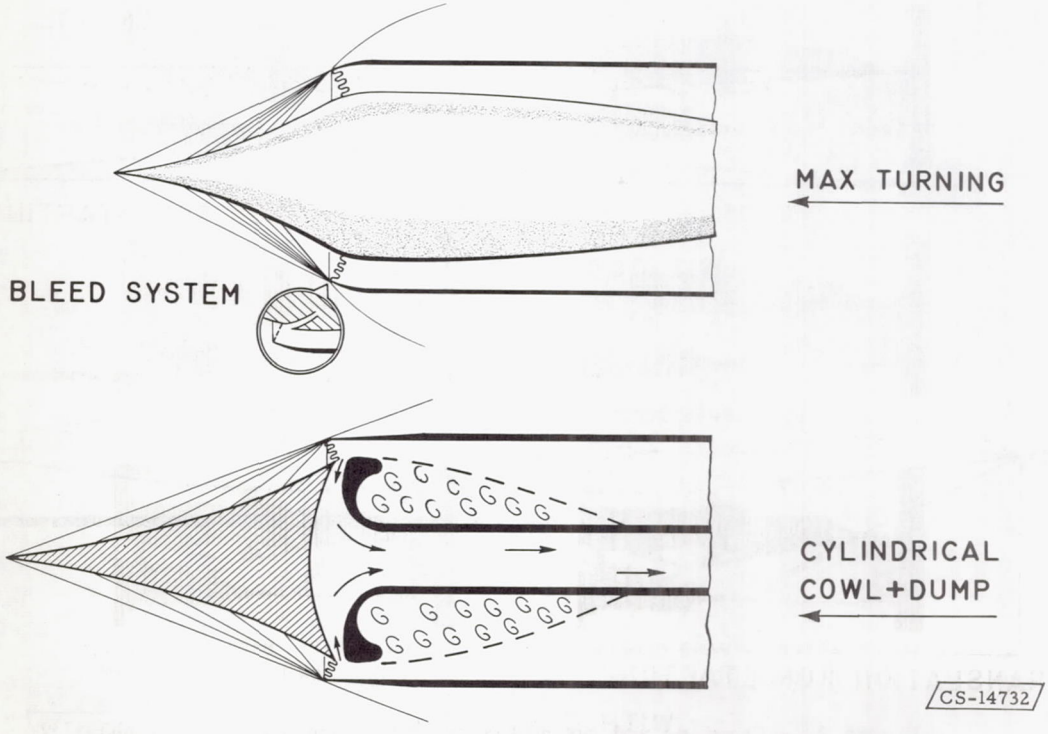


Figure 4. - External-compression inlets.

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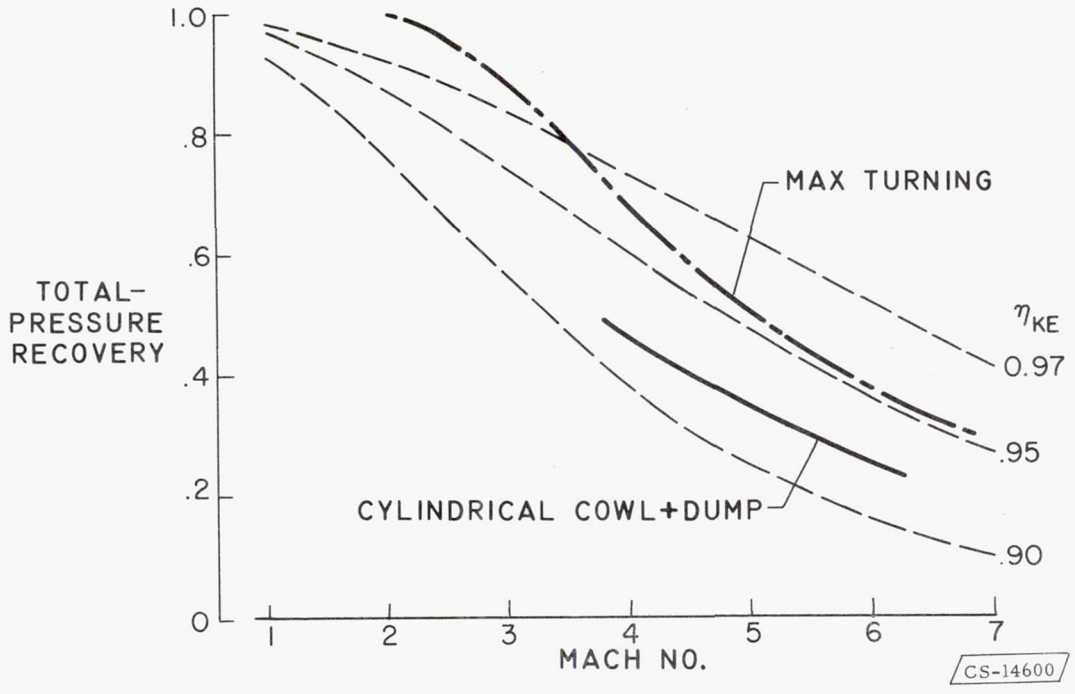


Figure 5. - Theoretical recovery limits for external-compression inlets.

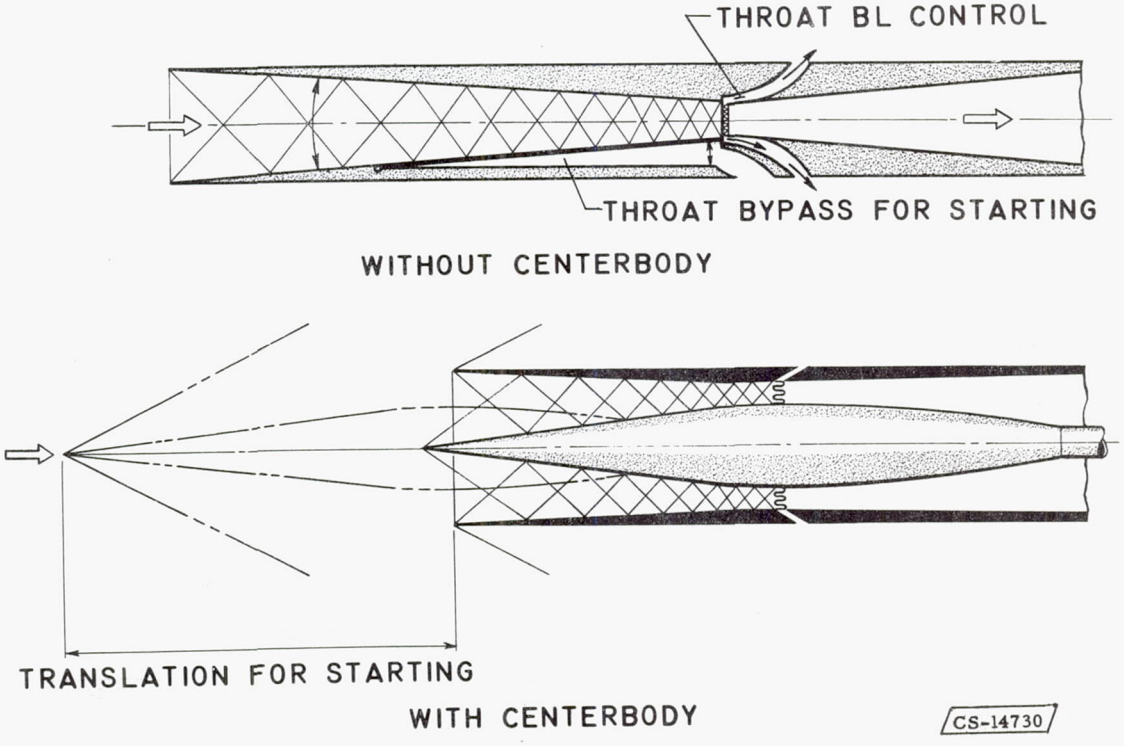


Figure 6. - Internal-compression inlets.

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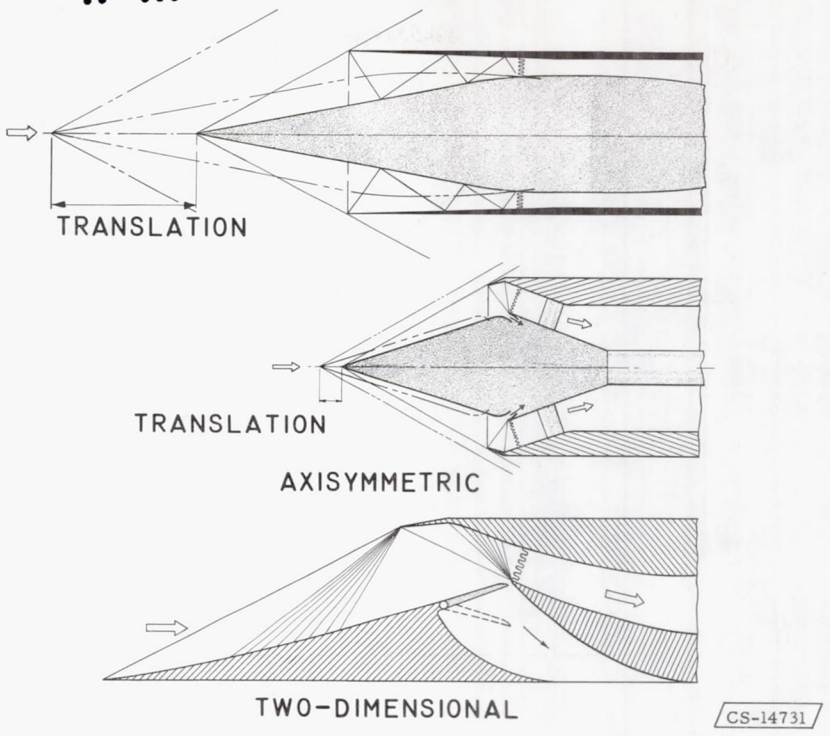


Figure 7. - Inlets with external and internal compression.

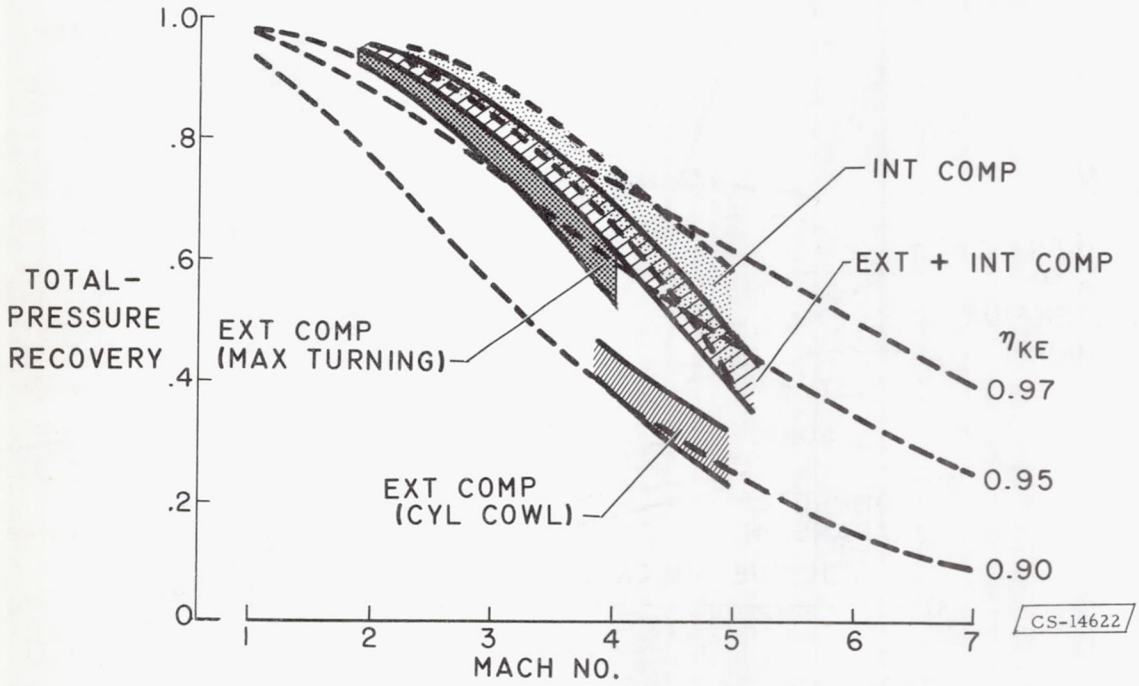


Figure 8. - Experimental pressure-recovery levels.

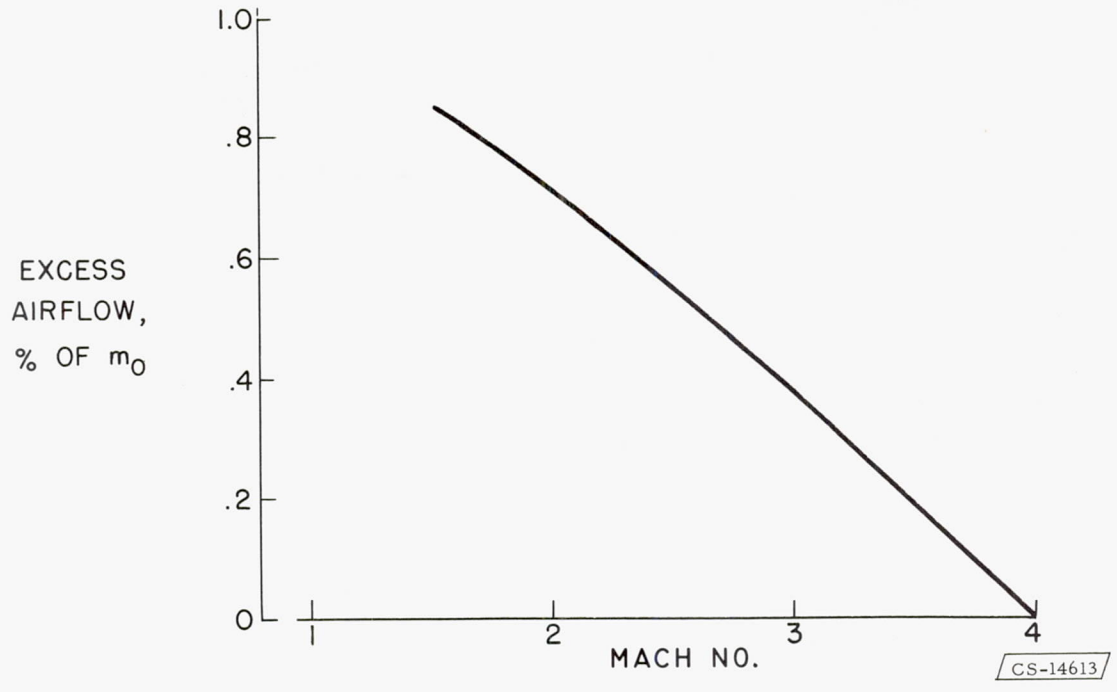


Figure 9. - Turbojet matching requirements. Design Mach number, 4.0.

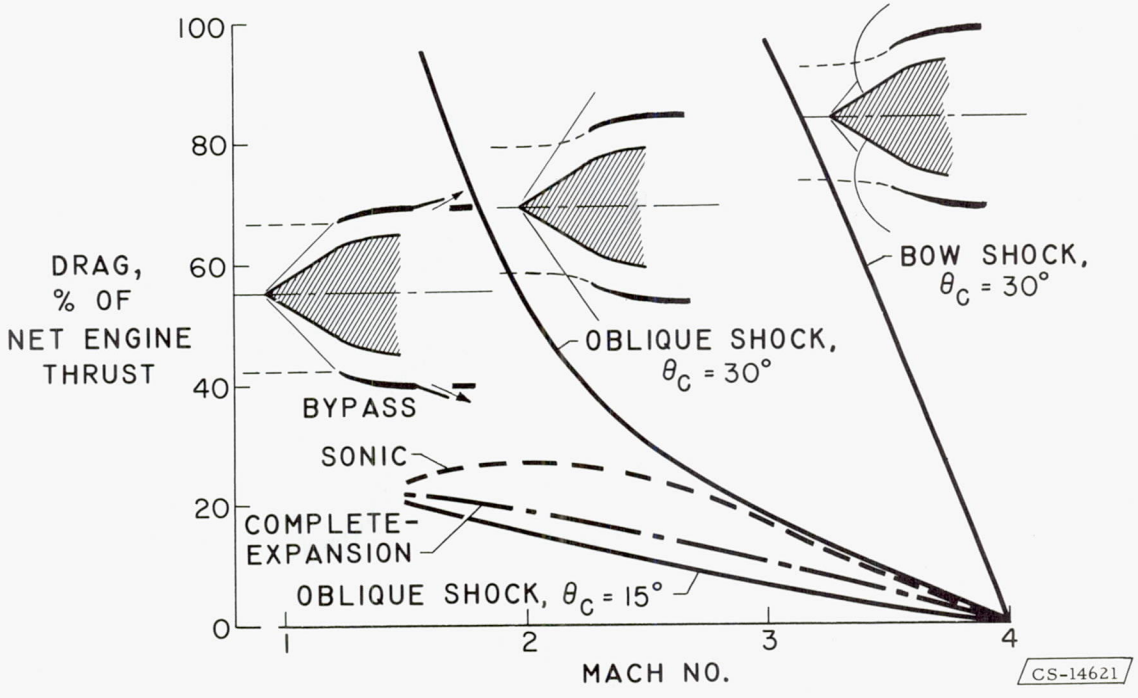


Figure 10. - Turbojet-matching drag penalties. Design Mach number, 4.0.

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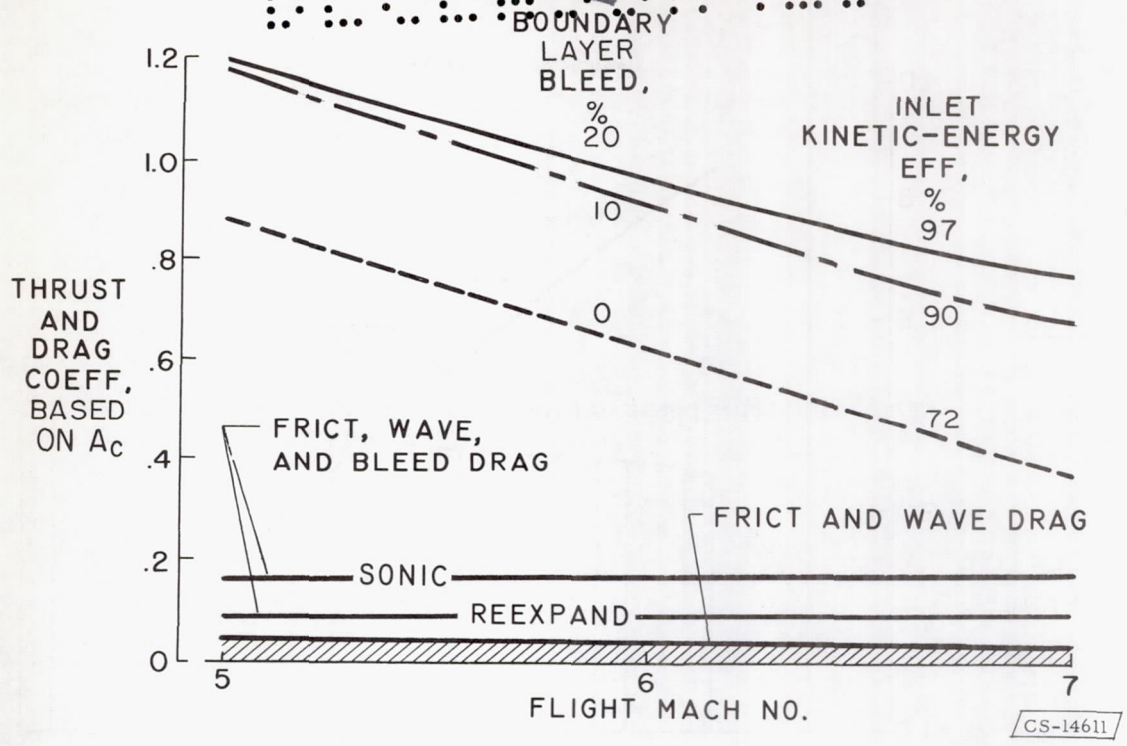


Figure 11. - Ramjet thrust and drag coefficients. Ratio of exhaust to ambient pressure, 2.5; velocity coefficient, 0.97; stoichiometric combustion of SF-1.

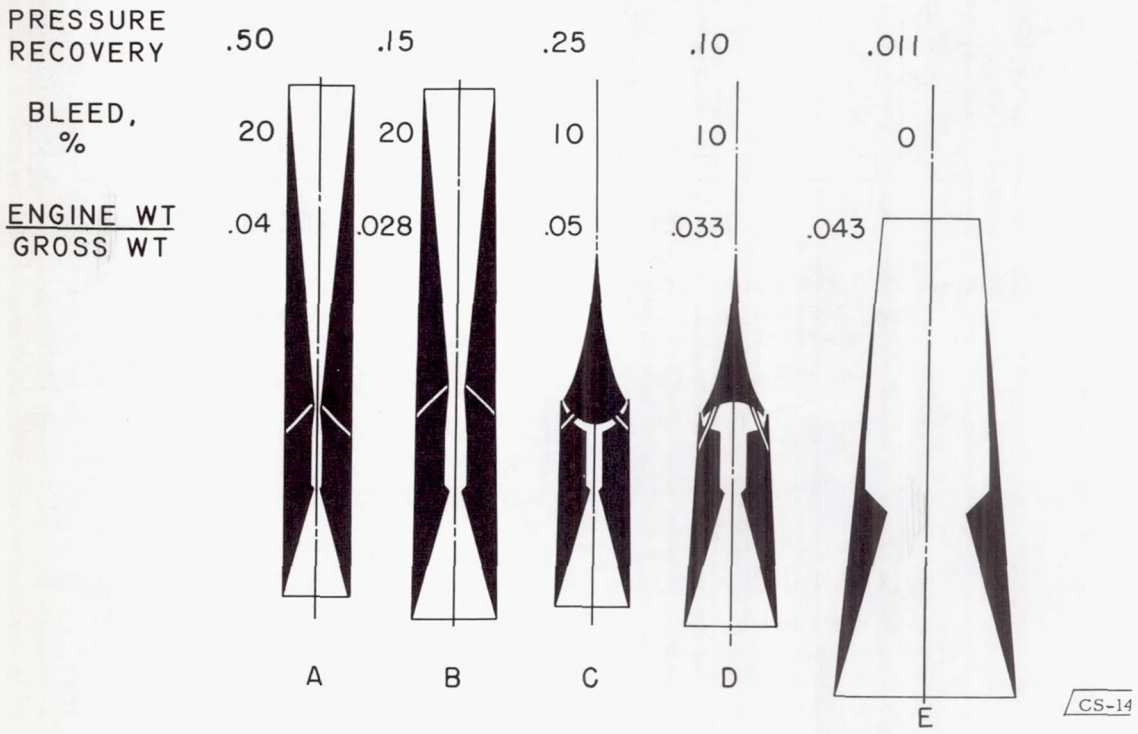


Figure 12. - Relative sizes for ramjets with equal net thrust. Mach number, 7.0; altitude, 100,000 feet.

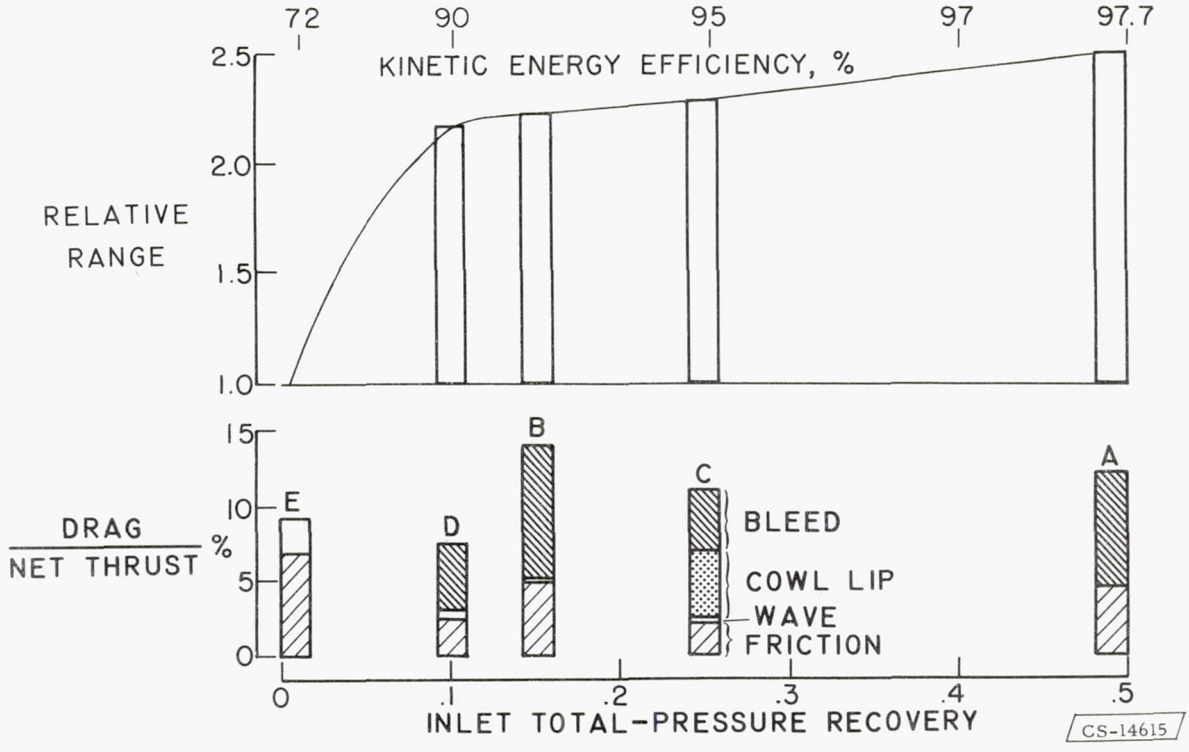


Figure 13. - Comparison of equal-thrust ramjets. Mach number, 7; altitude, 100,000 feet; ratio of exhaust to ambient pressure, 2.5; velocity coefficient, 0.97; stoichiometric combustion of SF-1.

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